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Evaluation of ecological impacts of synthetic natural gas from wood used in current heating and car systems

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Abstract

A promising option to substitute fossil energy carriers by renewables is the production of synthetic natural gas (SNG) from wood, as this results in a flexible energy carrier usable via existing infrastructure in gas boilers or passenger cars. The comprehensive life cycle-based ecological impact of SNG is investigated and compared with standard fuels delivering the same service (natural gas, fuel oil, petrol/diesel, and wood chips). Life cycle impact assessment methodologies and external costs from airborne emissions provide measures of overall damage. The results indicate that the SNG system has the best ecological performance if the consumption of fossil resources is strongly weighted. Otherwise natural gas performs best, as its supply chain is energy-efficient and its use produces relatively low emissions. Wood systems are by far the best in terms of greenhouse gas emissions (GHG), where SNG emits about twice as much as the wood chips system. The main negative aspects of the SNG system are NO_x and particulate emissions and the relatively low total energy conversion efficiency resulting from the additional processing to transform wood to gas. Direct wood combustion has a better ecological score when highly efficient particulate filters are installed. SNG performs better than oil derivatives with all the evaluation methods used. External costs for SNG are the lowest as long as GHG are valued high. SNG should preferably be used in cars, as the reduction of overall ecological impacts and external costs when substituting oil-based fuels is larger for current cars than for heating systems.

Keywords: Bioenergy; Biofuel; Energy system analysis; External costs; Greenhouse gas; Life cycle assessment; Natural gas; Wood gasification

1. Introduction

The ratification of the Kyoto Protocol to the United Nations Framework Convention on Climate Change emphasizes the need for an extended investigation of CO_2-low technologies for energy supply, in order to identify efficient substitutes of fossil energy sources. Within the sustainability programme Novatlantis of the Domain of the Swiss Federal Institutes of Technology (ETH), which pursues new technologies for a sustainable future in conurbations, PSI has investigated the potential of the use of gasified wood as a flexible and CO_2-neutral energy carrier. According to the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), 21 PJ/a of residual wood from forest could additionally be used for energy purposes in Switzerland [1]. From this wood, synthetic natural gas (SNG) [2] could be produced [3], and supplied to the natural gas network to substitute fossil natural gas for heating purposes or for powering a gas vehicle. Compared to the Fischer–Tropsch biomass conversion to a liquid fuel, SNG production from wood promises lower costs and also advantages for decentralized applications [4]. This technology is assumed to be in commercial use from 2012 and shall be compared with conventional fossil technologies and associated energy systems. In particular, this study deals with technologies delivering one energy service, i.e. space heating, using boilers fuelled by natural gas, oil, and wood chips (the latter for district heating), as well as transportation, using passenger cars, fuelled by natural gas and petrol/diesel. Cogeneration of heat and power is not addressed, as electricity substitution is not an issue for Switzerland, which has a practically CO_2-free supply. Furthermore, dealing with the allocation of environmental damage to the co-products, consideration

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of several fuels in standard cogeneration units in the comparison, and energy scenario analyses for substitution of heat and electricity would have implied major scope extension.

A comparison of greenhouse gas emissions (GHG) alone is insufficient for an assessment of the overall environmental effects (also including damage to human health) of technology choices. Assessment methodologies encompassing the full spectrum of the burdens associated with an industrial process or product are indispensable for identifying choices that comply with a comprehensive set of ecological criteria. The principle of life cycle assessment (LCA), also called cradle-to-grave analysis, is the consideration of all cumulative burdens stemming from the entire lifetime (construction, operation, and dismantling) of all industrial activities involved, directly and indirectly, in the production of goods or services. In the case of energy systems, full chains or cycles are analysed, i.e. from exploitation of natural resources, through processing of the energy carrier, its conversion to useful energy, and eventually waste management [5]. One considerable advantage of using LCA for ecological assessment of industrial processes is that databases covering different sectors including energy systems are being developed and updated worldwide, e.g. in Japan [6] and Switzerland [7], thus allowing a reliable and fair basis for comparing alternatives. The Swiss database ecoinvent v1.2 is used in the present study for data on reference energy technologies [8]. LCA has often been used in ecological labelling of products [9]. For the production and use of biogenic fuels for different applications, only few studies based on LCA have been published (e.g. [10], sole journal article to date), though data are available in databases (e.g. [11]), while others are more limited in scope (e.g. [12,13]). An LCA study on the production of SNG from wood has not been issued so far.

The full scope effects of technologies on the environment and human health are manifold, measured using diverse units, and often requiring trade-offs, which calls for consideration of subjective elements or societal choices to allow aggregation. Integration of environmental impacts of different nature into one score can be accomplished with life cycle impact assessment (LCIA) methods [14], as well as with the estimation of external costs [15], as will be shown in this paper along with the estimation of GHG from energy chains. Both methodologies are continuously updated and widely used by the respective scientific communities. Alternatively to full integration, environmental criteria may be kept separated and weighted against economic and social criteria using multi-criteria decision analysis (MCDA), thus representing explicitly the subjective preferences of stakeholders [16]. The latter method will not be applied nor discussed in this paper. From the above, an absolute answer from such comprehensive comparisons cannot be expected, but an analysis of robustness using different methods and different weighting schemes in parallel form a balanced basis for the choice among technology alternatives.

2. Methodology

2.1. Life cycle impact assessment

Some LCIA methods provide a single measure of the potential ecological effects of processes or products considering complete process chains, thus allowing direct comparison with alternative technologies. The application follows a procedure described in [5,14]. The basic idea of such LCIA methods is to use the cumulative inventories, which are mass flows describing energy and non-energy resource consumption as well as emissions to air, soil, and water, and multiply the resulting single elementary flows with substance-specific factors. The two LCIA methods used in this investigation, Eco-indicator '99 (EI'99) [17] and Eco-scarcity [18], have been chosen because of their wide acceptance within the LCA community and their broad scope.

The EI'99 method was developed by PRé Consultants in Amersfoort, Holland, and describes environmental effects for emissions occurring in Europe. It is a damage-oriented method, which considers, by means of damage factors, the effects of all emitted or used substances in three damage categories: human health, ecosystem quality, and resources (fossil and mineral). The different damage categories are normalized, then further weighted on the basis of the perspective of three typologies of stakeholders, identified using a cultural theory concept [17]: Individualist, Egalitarian, and Hierarchist. The Individualist has a short-term perspective and only accepts proven effects; human health is most important, whereas the use of fossil resources is not perceived as a problem and therefore not valued. The Egalitarian has a long-term perspective and allows inclusion of potential effects even with a minimum of scientific evidence; ecosystem quality is most important. The Hierarchist has a balanced time perspective and requires consensus among scientists for inclusion of a burden; this perspective is considered the closest to the scientists' point of view. Table 1 shows the damage categories and the rounded weighting factors by cultural perspective, as suggested by the authors of the method [17]. For the Hierarchist perspective, we adopt the average weighting factors along with ecoinvent [19].

The characterization of subjective elements has been derived from the observation of actual behaviour and analyses of how decisions on comparable issues are taken by those types, and the weighting has been determined using a questionnaire [17]. The resulting scores are summed up to give one single total score.

The Eco-scarcity method [18] is applicable to Swiss conditions. Conceptually, it is a distance-to-target model, comparing current flows to the environment with target values or critical flows, which are intended to be based on scientifically sound political objectives, for example Swiss emission limits. However, for the storage of radioactive waste, which has a relatively large influence on the results when nuclear-based electricity mixes are used, a rough limit

Table 1
Most important inventory items (resource use and emissions to air, ground, and water), damage analysis midpoint and final categories, and weighting schemes per cultural perspective for Eco-indicator '99

Life cycle inventory	Damage analysis midpoint categories	Damage categories	Individualist (%)	Egalitarian (%)	Hierarchist (average; %)
Land use: occupation and transformation	Regional effect on vascular plant species Local effect on vascular plant species	Ecosystem quality	25	50	40
NO_x, SO_x, NH_3	Acidification/eutrophication				
Pesticides, heavy metals	Ecotoxicity				
CO_2, CH_4, N_2O, HCFC	Climate change	Human health	55	30	40
H/CFC, halons	Ozone layer depletion				
Nuclides	Ionizing radiation				
NO_x, SO_x, VOC, particulates	Respiratory effects				
Heavy metals, PAH, dioxins, etc.	Carcinogenesis				
Extraction of minerals and fossil fuels	Surplus energy for future extraction	Resources	20 (mineral only)	20	20

has been arbitrarily defined by the developers of the method, based on the Swiss nuclear waste policy in the late 1990s [18]. There are no damage categories in Eco-scarcity. Another important difference compared to EI'99 is that land use is not included in the weighting, as critical flows cannot be defined. The product of a certain mass flow and the corresponding weighting factor gives the specific UBP (Umweltbelastungspunkt; Environmental Impact Point); these UBPs are summed up to give a single score.

2.2. Greenhouse gas assessment

The examination of GHG is included, as the curbing of their emissions must be pursued by energy decision makers as required by the Kyoto Protocol. The assessment is conducted for entire energy chains, and performed applying the IPCC 2001 [20] radiative forcing values of different species of GHG, relative to CO_2. The cumulative GHG emission gives an implicit measure of the total life cycle impact of a technology on climate change. It needs to be noted that the inclusion of industrial activities beyond national boundaries does not allow direct application of LCA results to national implementation of GHG emission curbing programmes. At any rate, GHG emissions are included in both LCIA and external cost evaluations.

2.3. External cost assessment

A measure of damage that appeals to several stakeholders and energy decision makers is the "external cost", since they usually understand monetary values better than any other unit and can relate them to system private costs. External costs are normally not included in the direct costs of a technology. Total costs are obtained by internalizing external costs, thus providing an economic indicator that better represents the sustainability of the technology than just the private costs, and can more efficiently assist in decision making by means of cost–benefit evaluations of alternative options. Since the early 1990s, the European Commission has supported a series of studies, named ExternE, for the estimation of external costs of energy [15]. The ExternE-Pol project included a task combining detailed life cycle inventories of complete energy chains associated with current and new energy technologies with damage factors for airborne emissions based on the impact-pathway approach [21] or determined in previous projects of the series. The LCI cumulative results do not contain information on the location of the emission sources. Therefore, the external costs were calculated based on damage factors for stack emissions in an average location in each of the 15 member countries forming the European Union (EU15), where most of the modelled industrial activities of concern take place. The factors refer to the most important airborne pollutants, and take into account the advances up to 2004 of the external costs methodology within the ExternE series (Table 2). Possible changes of the factors in future due, example, to different background pollutions are not considered here. We do not expect any changes in the ranking of the systems due to the future background issue. Damage factors for the exhaust from car operation have been treated separately from damage factors from stack emissions and other sources. Vehicle operation-specific average factors for ground level emissions were used, taking into account local effects due to SO_2 and $PM_{2.5}$ in different emission locations. Population density plays a major role for the calculation of total health damages. To represent an average mix route, combining urban and highway/rural roads, 38% of the emissions were assumed to be released in an urban environment. The set does not differentiate between different particle and SO_2 damage factors for petrol and diesel, as this would not introduce remarkable changes in the results. Damage from PM_{10} particulates is practically due to the $PM_{2.5}$ fraction. For this reason, only the $PM_{2.5}$

Table 2
Base damage factors in Euro (year 2000) per kg of pollutant emitted in average locations within the EU15 countries [21]

Species	Damage factors (€$_{2000}$/kg)	
	Stacks	Car operation
CO_2-equivalent	0.019	0.019
SO_2	2.94	4.6
NO_x	2.91	3.2
$PM_{2.5}$	19.54	178 (combustion) 119 (abrasion)
Arsenic	80	—
Cadmium	39	—
Chromium-VI	240	—
Lead	1600	—
Nickel	3.8	—
Formaldehyde	0.12	—
NMVOC	1.12	1.1
Radioactive emissions	50,000[a] (€$_{2000}$/DALY)	—

[a]Disability-Adjusted Life Years (DALY), assumed equal to the unit value of chronic Years Of Life Lost (YOLL).

fraction is considered here. Along with EI'99, the Disability-Adjusted Life Years (DALY) concept has been used as a measure of the potential damages from ionizing radiation. The monetary value of one DALY was set equal to the current ExternE monetary value of a life year [21].

3. Compared technologies and system boundaries

Table 3 shows key information on the compared heating and car systems.

Data source for all conventional processes is the Swiss online LCA database ecoinvent v1.2 [7,8,24,25]. These data, describing standard technology in Western Europe around the year 2000, are used as an approximation for the year 2012, when the Kyoto protocol will take effect and SNG plants should be operational. The efficiency of the oil and gas boilers is not expected to change significantly in this decade. The ecoinvent database is also used for describing ancillary industrial services, like material manufacturing and construction machines, thus providing a consistent background for comparison of energy systems.

The SNG gas heating system is compared with fossil gas and oil heating systems. Each of them uses a boiler size of about 10 kW, which is typical for a single family house. To gain heat, the wood could alternatively be burned directly. For wood chips combustion, we assume an efficient district heating plant of 1 MW (as order of magnitude) supplying a heat distribution network. The plant uses a standard cyclone separator with a particle removal efficiency of about 50 wt%. Total heat losses for the district heating network from the furnace to the distribution point within the building amount to 11% on the average [26]. Wood pellets have not been taken into consideration since their fabrication uses a by-product of industrial wood (sawdust) and therefore a different wood resource.

Table 3
Main characteristics of the compared heating and car systems

System	Heating systems				Car systems		
	Wood chips district heating	SNG heating	Fossil gas heating	Oil heating	SNG car	Natural gas car	Petrol/diesel car
Energy source	Wood chips	SNG from wood	Fossil gas	Oil	SNG from wood	Natural gas	Petrol/diesel
Combustion device	Furnace 1000 kW	Gas boiler 10 kW modulating	Gas boiler 10 kW modulating	Oil boiler 10 kW non-modulating	Internal combustion engine, based on average passenger car in Switzerland in the year 2000 (ecoinvent)		
Emission data	Ecoinvent	Measurements Güssing; PSI; ecoinvent	Ecoinvent	Ecoinvent	'Clean Engine Vehicle' EMPA [22], 'Ökoprofile von Treibstoffen' BUWAL [23]		Average car in use 2010 [25], 8% diesel
					Fuel-independent emissions: ecoinvent		
Fuel efficiency [MJ/MJ$_{fuel}$; MJ$_{fuel}$/km]	85%	96%	96%	94%	1.87	1.87	2.54
Cumulative energy demand [MJ-eq./MJ; MJ-eq./km]	1.91 (fossil: 0.08)	2.78 (fossil: 0.11)	1.26	1.39	5.04 (fossil: 0.2)	2.24	3.39
Functional unit	MJ	MJ	MJ	MJ	pkm	pkm	pkm

The system boundaries for the SNG heating system are determined by the complete process chain, starting with the wood growing in the forest, and ending with the production of useful energy at the boiler before distribution in the house (Fig. 1). For each process step, its relevant energy and resource consumptions, the land use as well as the available emission species are accounted for. Consistently, the boundaries for fossil systems also include the full energy chain, as described above. The functional unit for heating systems is 1 MJ of useful heat before distribution in the house.

The SNG fuelled passenger car is compared with a fossil gas car and a petrol/diesel car. The latter represents an average oil-based passenger car, with a diesel share of 8% (average for cars currently circulating in Switzerland) [25]. Data on infrastructure are taken from the ecoinvent database and is common for all car systems analysed here. It includes construction, maintenance, and disposal of car and road; for the gas car body, a compressed gas tank replaces the liquid fuel tank [27]. Data also include fuel-independent operational car emissions like particulates from tyre and brake abrasion as well as road resuspension [25]. Emission data for the combustion of petrol/diesel and gas in cars (SNG and natural gas are assumed to have the same composition) are an estimation for average cars in 2010 [21–23].

The analysis is source-to-wheel, i.e. for SNG, the system boundaries include all processes from wood growing and chipping in the forest up to the production of the useful energy service in the form of passenger-kilometres (pkm).

As stated previously, the scope of this analysis is limited to heating and transport systems, delivering one energy service only. Therefore a wood-based combined heat and power (CHP) plant delivering heat and electricity has not been included, although it represents an efficient alternative use of wood.

4. Gasification and methanation of residual wood

Fig. 1 shows the process chart for the wood-based SNG heating system, with more details provided for the transformation of wood to gas.

The wood chips are produced with a wood chipper from residual wood in the forest. They are assumed to be delivered to the plant with a humidity of 50% over an average transport distance of 25 km by lorries in Switzerland. The SNG plant has an expected production capacity of 28 MW_{th} SNG (corresponding to 50 MW_{th} input energy wood) and runs approximately 7000 h/year. Its infrastructure is estimated scaling down the data of a larger methanol production plant, assuming that the material use changes linearly with the throughput. The assumed lifetime for the plant is 30 years.

The production of methane from wood consists of two main separated processes, namely the gasification of wood and the methanation of the wood gas, followed by cleaning and conditioning procedures. Efficiency, operational use of energy, resource consumption, and emissions are estimated based on measurements at the CHP pilot plant in Güssing (Austria) for the gasification part, and results from the ongoing PSI research for the methanation part using a 10 kW pilot reactor. They represent current state-of-the-art reference values.

Gasification is performed using the Fast Internally Circulating Fluidized Bed (FICFB) principle [28]. In the first section of the reactor, biomass is gasified with steam. Unconverted biomass (char) is transported to the second section together with bed material (olivine), where it is combusted completely with air. The heat released thereby is transported with the circulating bed material back to the first section where it keeps up the steam gasification. The product gas is composed of about 30–45% H_2, 20–30% CO, 15–25% CO_2, 8–12% CH_4, and 1–3% nitrogen [28]. The emission data used are average values measured on 21 February 2004 in Güssing [29]. The cold gas efficiency, defined as (fuel gas output)$_{th}$/(biomass input)$_{th}$,, depends mainly on the gasification temperature and the humidity of the biomass. At a gasification temperature of 850 °C and a wood humidity of 15%, the cold gas efficiency is about 73% [29], which is a somewhat optimistic value. Lowering the temperature and drying the wood chips increases the efficiency. From the gasification as well as the exothermic methanation part, waste heat is available, which is sufficient for drying the wood to the desired 15% humidity [30], requiring about 4 MW_{th}. Undesired traces of tar (1.5–2.5 g/N m^3), ammonium (about 1000 ppm), and dust (10–20 g/N m^3) [28] are removed from the gas by scrubbers and fed back into the gasifier.

Afterwards, the gas is compressed to about 2 bar by a blower. The gas still contains traces of H_2S, about 50–150 ppm [28]. The sulphur is absorbed by a ZnO bed, to form ZnS. ZnO can be regenerated by a reaction of ZnS with oxygen contained in air. Thereby, SO_2 is formed which can be converted with calcium carbonate into calcium sulphate, which is finally deposited in a sanitary landfill.

In the catalytic methanation stage, the C-containing substances are transformed into methane and CO_2. The CH_4 yield rises with increasing pressure and falling temperature. CO_2 is separated from the gas mixture using a membrane separation unit. The final composition used for the following calculations is 97.3 vol% CH_4, 2.6 vol% CO_2, and 0.1 vol% H_2O. This composition complies with pipe-line grade natural gas. The assumed efficiency of methanation, including losses for CO_2 separation, is 76.5% [30], which may be somewhat lower than achievable. For the methanation, a catalyst is used, which consists of aluminium oxide and nickel (50 wt% each). The amount needed is 100 gram, which has to be replaced about every 5000 h [30]. Aluminium oxide and nickel are assumed to be recycled. Recycling quotes for nickel are about 98% [31]; for aluminium oxide the same number is used. During methanation, the gas is compressed to the gas network pressure (30–70 bar), for which additional energy is needed

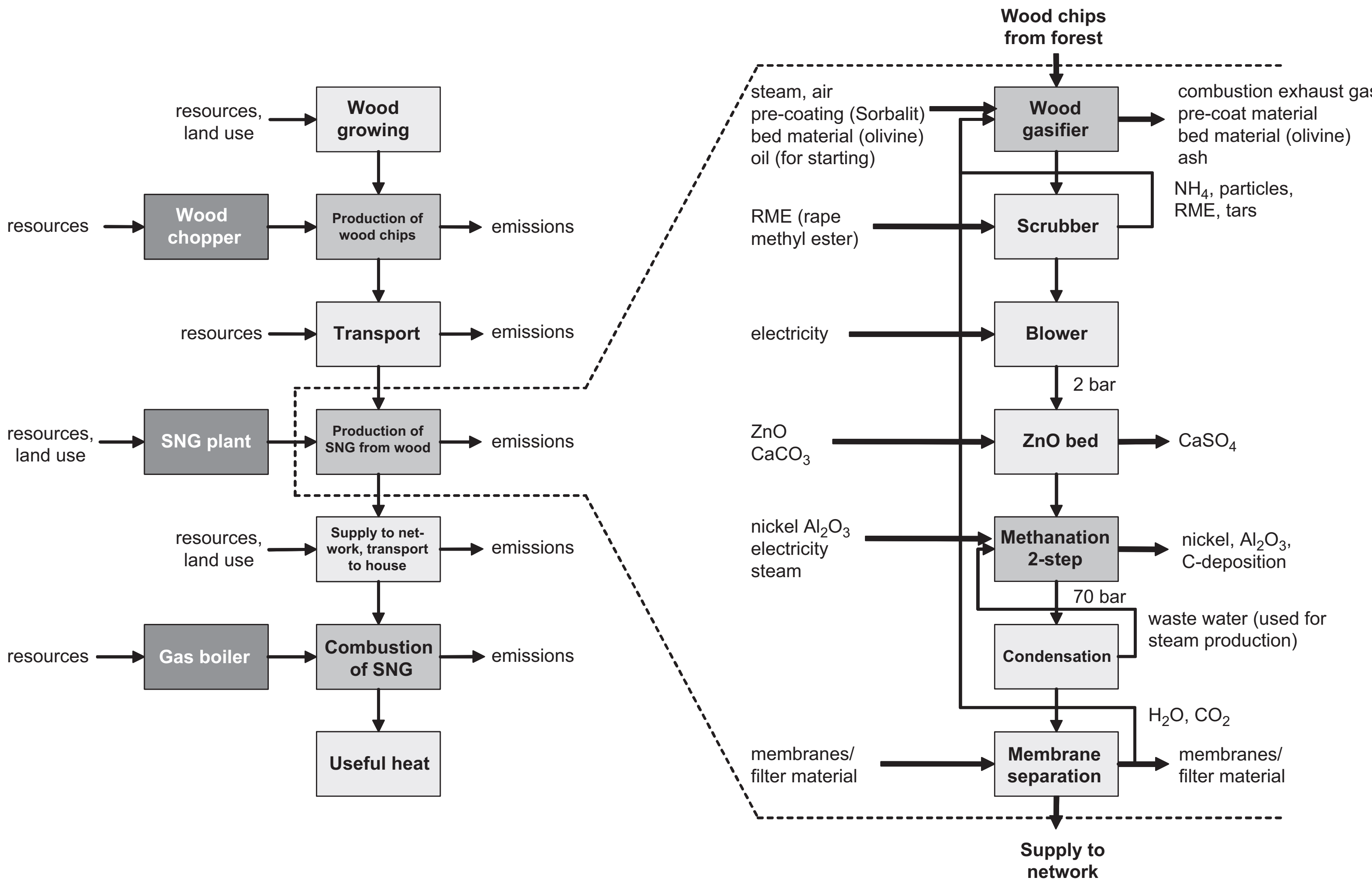

Fig. 1. Flow chart of the wood-based SNG heating system and detailed flow chart of the production of SNG.

(about 0.2 kWh/m^3 for a compression to 70 bar). This energy is assumed to be supplied by the Swiss electric grid. For the gas filling station, the gas has to be compressed additionally to 250 bar, which is assumed as a maximum pressure in the car tank.

In summary, the process for the production of SNG from wood can be described with the inputs and outputs shown in Fig. 2. The total thermal conversion efficiency of 56% is the product of the efficiency assumed for gasification (73%) and the efficiency assumed for methanation (76.5%).

5. Results

5.1. Comparison of heating systems per MJ of useful heat

The four LCIA weighting schemes produce distinct qualitative differences (Fig. 3). Using the EI'99 Hierarchist and Egalitarian perspectives, which strongly weight the use of fossil resources, the SNG gas heating system has the lowest environmental impact score of the four compared heating systems. The main constituents of the score are particulate emissions (wood chips production (mainly $PM_{2.5}$), electricity and mineral production (PM of all sizes)), NO_x emissions (mainly from forest activities and wood gasification), and the occupation of a large land area (mainly the used forest area). The wood chips district heating emits a relatively large amount of particulates (mainly $PM_{2.5}$), which originates around 50% of the total Eco-indicator points. The use of fossil resources results in the elevated score for the natural gas and oil heating system.

When non-renewable fossil resources are weighted low or zero (Eco-scarcity and EI'99 Individualist, respectively), the natural gas heating exhibits the lowest score, as it is a rather efficient system. The largest component of its score is CO_2. Using the EI'99 Individualist perspective, the SNG heating system has a distinctly higher score than natural gas because of particulate emissions, land occupation, and the relatively large use of metal resources. The latter, which become strongly weighted when using the Individualist perspective, are mainly needed for the production of wood chips (saw-chain replacement) and for the gas boiler.

With Eco-scarcity, the SNG heating system also exhibits a higher score than the fossil gas heating system mainly because of NO_x and particulate emissions, as well as the requirement of external electricity. If this electricity is supplied by the Swiss mix, which contains nuclear power (share about 40%), the volume occupied in geological repositories by high and medium radioactive waste including canisters, which is relatively strongly weighted in Eco-scarcity, leads to a higher score. If the process will be optimized for energy-autonomous operation, e.g. in case electricity would also be produced at the plant, the ecological assessment should be reworked.

Although the use of SNG generates lower direct emissions from its combustion compared to the direct

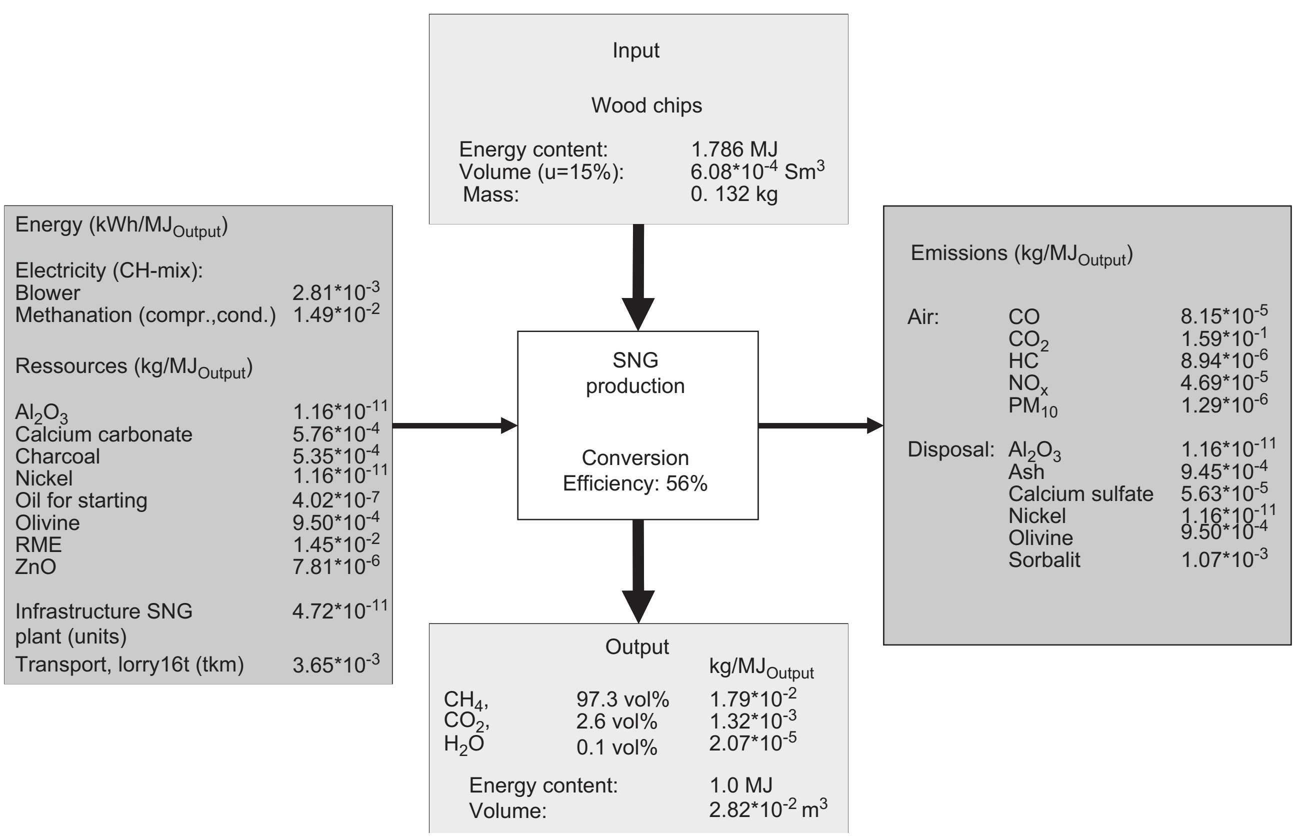

Fig. 2. Inputs and outputs for the production of SNG from wood.

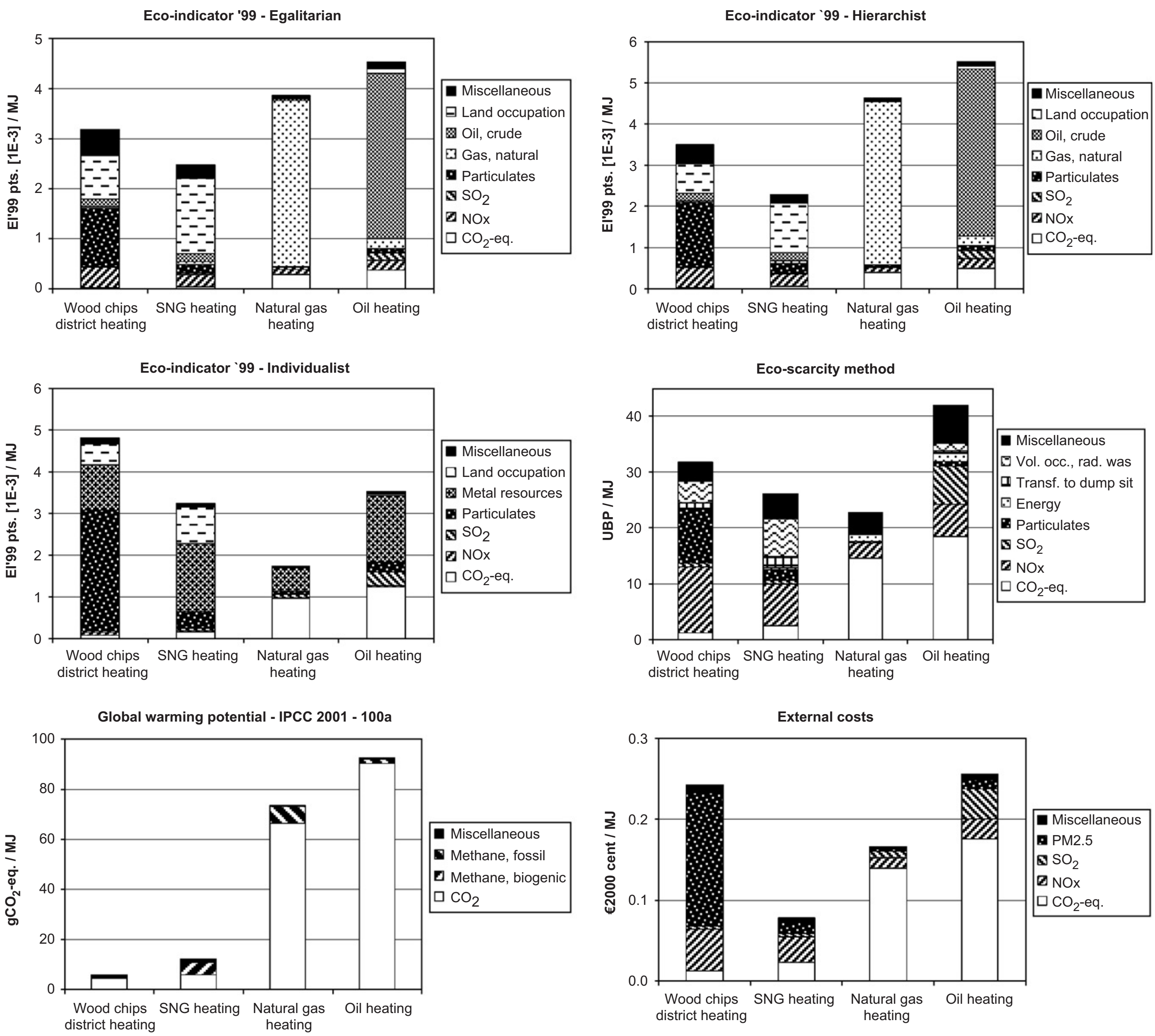

Fig. 3. Comparison of the results for the four heating systems, using the Eco-indicator '99 perspectives (Hierarchist, Egalitarian, and Individualist), the Eco-scarcity method, the radiative forcing values, and external costs, with breakdown of the major contributors.

combustion of wood, the increased number of intermediate processes before combustion generates environmental burdens. For example, production of rape methyl ester, used as washing agent, contributes 5–10% to total EI'99 score for the three perspectives and 4% to UBP. However, with all LCIA methods and weighting schemes, the SNG heating system has a lower score than the wood chips district heating and oil heating systems.

Land occupation has a substantial influence for wood-based systems when using the EI'99 method (see Fig. 3) because the wood is drawn from a relatively large forest area. This effect is larger for SNG. It can be argued that since the provided amount of wood is residual wood grown in already used forests, which supply industrial wood, the actual land use is not an addition, and the species diversity, which is the ecosystem quality described by the EI'99 land use sub-category, should not be further affected. As long as no previously unused forests are used for energy wood production, the results could therefore be modified by giving weight zero to land occupation.

Sensitivity calculations for the efficiency of the SNG production process show that for the EI'99 Hierarchist and Egalitarian perspectives, the score for the SNG heating system remains below the scores of the other systems for total gasification efficiency down to 40% and 47%, respectively, from 56% assumed in the present study. With the Individualist perspective, a lower efficiency of about 54% would lift the score up to the level of the oil heating system. Within the interval 40–80%, the SNG score remains in between the scores of the wood chips district heating and the fossil gas heating system. Using the Eco-scarcity method, a reduction of the efficiency to about 50%

increases the score of the SNG heating up to the level of the wood chips district heating, a further reduction to 42% up to the level of oil.

The wood chips district heating system has a relatively high LCIA (and external cost) score because of high particle emissions (Fig. 3). With an electrostatic filter, which can technically reach a removal efficiency of more than 99%, also reducing the finest, from the human health point of view most damaging, particulates ($PM_{2.5}$), the weighted LCA scores would drop below the scores of the SNG heating system with all the weighting schemes used. The implementation of highly efficient particulate emission control technology is at present not encouraged by the Swiss emission standards, which can be met with a less-expensive cyclone filter.

The calculated radiative forcing potential (IPCC 2001) shows the expected result that the renewable systems perform distinctly better than the fossil systems. The SNG heating system has about twice the cumulative GHG emissions of the wood chips district heating system because of the lower overall energy chain efficiency, substantial methane emissions, and the increased use of ancillary processes for the production of the gas.

The SNG ranking obtained for external costs is the best among the analysed technologies, whereas oil boiler and wood chips furnace rank worst. The relative contribution of GHG is very high for oil and natural gas. As a sensitivity case dictated by the large uncertainty of GHG damage factors, if GHG would be valued low, e.g. 1 €$_{2000}$/kg [21], natural gas would perform best, SNG second best, in-between gas and oil, whereas the external costs for the wood chips furnace would change only a few per cent from the base case value.

5.2. Comparison of passenger car systems per passenger-kilometre

The LCIA method EI'99 with Hierarchist and Egalitarian perspectives produces dissimilar ranking of the passenger car systems from EI'99-Individualist and Eco-scarcity (Fig. 4). One central reason is the different relative importance calculated for the infrastructure. Depending on the weighting method, the infrastructure originates 62–87% of the total score for the SNG car, whereas for a petrol/diesel car this share is in the range of 39–85%, because of the higher impact of the fuel (supply chain and combustion) and the lighter fuel tank. All cars are assumed to operate 150,000 km during their lifetime.

The SNG car system has a lower score than the petrol/diesel car system with all used LCIA schemes except the EI'99-Individualist perspective. The main reasons for the advantage of SNG over petrol/diesel are the use of a renewable energy source, low net CO_2 emissions, and lower NO_x and SO_2 emissions. On the other hand, it has elevated particulate emissions (wood chopping and gasification), increased total land occupation (prevalently forest area), a

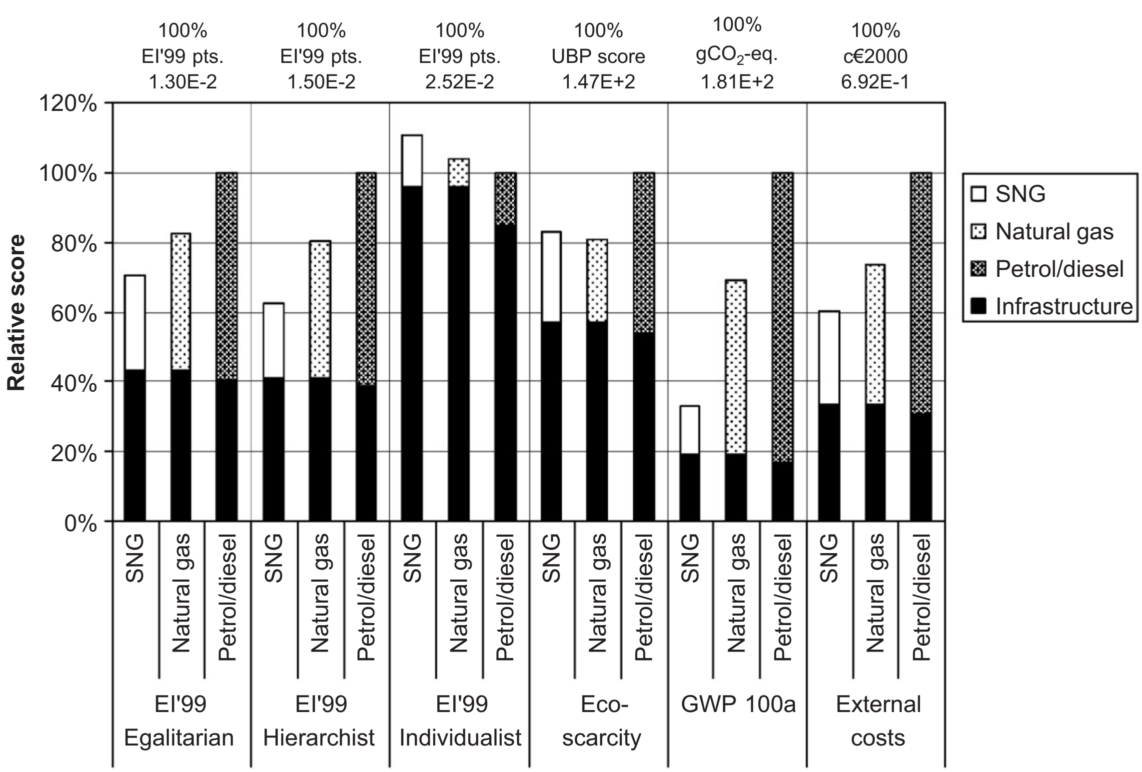

Fig. 4. Relative score of Eco-indicator '99 and UBP points, kg CO_2-equivalents (global warming potential) and €$_{2000}$ cents (external costs) per pkm for the SNG, natural gas, and petrol/diesel car, relative to total of the petrol/diesel car; the shares of the fuel part (supply chain and combustion) and the infrastructure (construction, maintenance, and disposal of passenger car and road) are given separately. Numbers at top are absolute scores, each corresponding to the petrol/diesel system, set at 100%.

higher indirect production of radioactive waste through the use of the Swiss electricity supply mix for the gas compression (weighted in Eco-scarcity) and a higher use of metal resources (for the compressed gas tank and in forestry, e.g. saw-chain replacement). The latter produces a significant difference when applying the EI'99-Individualist perspective, which gives superior weight to mineral resource consumption, resulting in a better score for the petrol/diesel car system with respect to gas cars.

The natural gas car system scores less ecopoints than the petrol car system, with all the weighting schemes except EI'99-Individualist. This is analogous to the results for the heating systems. The analogy is also apparent when comparing SNG from wood with natural gas as car fuel. When strongly weighting the use of fossil resources (EI'99 Egalitarian and Hierarchist perspectives), the SNG car exhibits a better ecological performance than the natural gas car; when the weight is zero (EI'99 Individualist perspective) or small (Eco-scarcity), the energetically more efficient natural gas supply chain leads to a lower score for the natural gas car.

The relative scores obtained for external costs approximately match the EI'99 Egalitarian and Hierarchist schemes (Fig. 4). Also with external costs, the infrastructure contributes substantially to the total score. GHG contribute 27%, 47%, and 49% to the total external costs for SNG, natural gas, and oil-derived fuels, respectively. In case GHG would be valued low, e.g. 1 €$_{2000}$/kg [21], the score for SNG burned in cars would be slightly above natural gas, but still distinctly below oil.

5.3. Ecologically preferable use of SNG

As discussed above, SNG gained from the available energy wood resources could be applied for heating purposes as well as for powering a passenger car. As these services and hence the functional units are different, the results shown above cannot be cross-compared directly. In order to be able to make a statement about the best use of SNG from an ecological point of view, the effects of using SNG for substituting oil-derived fuels in current technologies are compared. The comparison is performed using a scenario with 20 PJ/year of residual wood used for gasification; this primary energy is defined as the functional unit. The energy wood input generates a certain amount of useful energy when converted to SNG and burned in a heating or car system. The total ecopoints, CO_2-equivalents, and external costs per MJ of the SNG and oil heating, and per pkm of the SNG and petrol/diesel car are multiplied with the respective total amount of energy services produced by the SNG system. Then, the difference between the renewable SNG system and the oil system is calculated, which gives a measure of the total reduction of ecological impacts by substitution. Here, the assumed reference systems are the year 2000 oil boiler for heating [8] and year 2005 average EU15 passenger cars [21]. Fig. 5 shows the results of these calculations for all methodologies and weighting schemes discussed in this paper. Avoided points are given in relative terms to the respective values for car systems, whose absolute amounts are reported on top of the picture. Apart from EI'99-Individualist, results for all methods agree that SNG should preferably be burned in cars rather than in boilers. The two main reasons are:

(a) Process specific—the lower energy investment for producing heavy oil or diesel vs. petrol in refinery (ratio 1:1.8 [32]).
(b) Assumption specific—the relatively low efficiency of the car fleet to substitute. The ratio of the tank-to-wheel efficiency of the current petrol/diesel car to the modelled future gas car is 1:1.19 [21–23,25], which results in higher fuel consumption and emissions for the oil-derived fuels.

The difference in car efficiency originates from the further developed engine technology of the gas car analysed in the Clean Engine Vehicle study [22] and to some extent also from the below-average size of the modelled gas car. The latter difference leads to a small bias favouring gas, but modelling average size gas cars would not change the qualitative results. The efficiencies of the compared boilers are at about the same level, oil vs. gas 1:1.02. In conclusion, the analysis of saved ecopoints expresses the fact that the relative improvements of the efficiency of heating systems are expected to be very small compared with the room for improvements of the efficiency of future cars vs. current models. The infrastructures for all systems and also the wood supply chain for SNG do not play a significant role in the comparison of saved damages unless a strong weight is given on mineral resource consumption (EI'99-Individualist).

6. Conclusion

LCA and external cost evaluation allow comparisons of the overall ecological impact of the use of SNG produced from wood in heating and car systems vs. different fuels burned in technologies delivering the same services. Greenhouse gas accounting of entire energy chains also leads to meaningful technology ranking under consideration of the importance attributed by energy policy-makers to the Kyoto Protocol. The applied assessment methods lead to somewhat different results with respect to technology ranking due to the different scopes and the partially subjective nature of aggregation of impacts. However, they provide sufficient arguments for supporting ecologically benign choices.

The analyses using the LCIA method EI'99 show that when the use of fossil resources is strongly weighted, the SNG heating system ranks best among the heating systems compared. With a low weighting of the use of fossil resources, the natural gas heating system has the lowest impact score because of the energetically efficient supply of

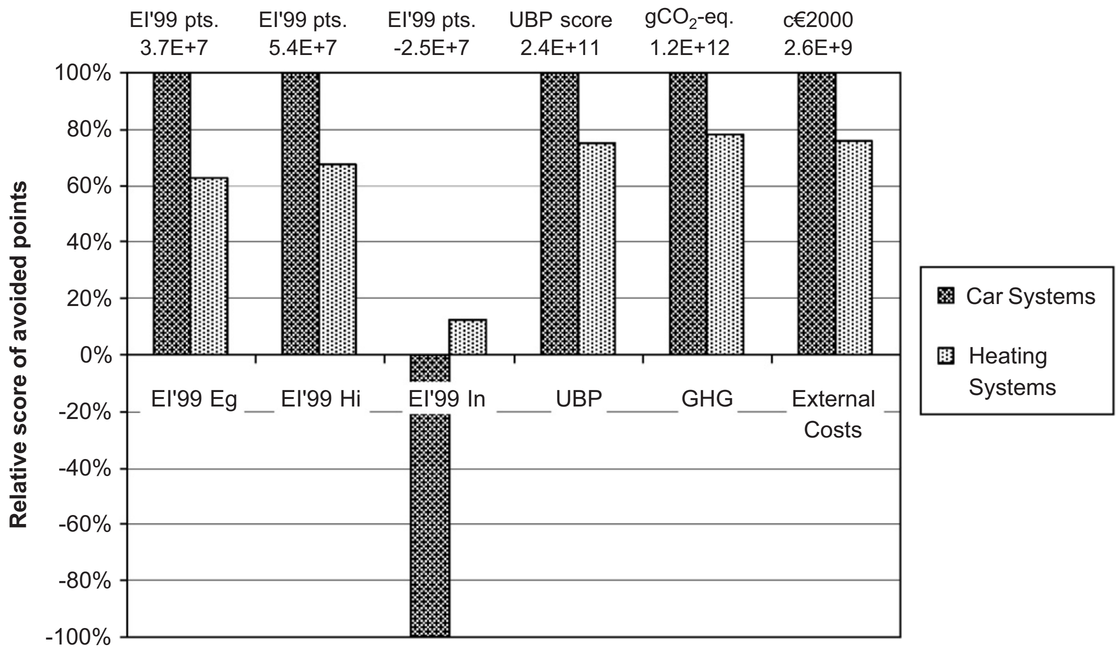

Fig. 5. Avoided Eco-indicator ’99 (EI’99) and UBP points, LCA-based GHG, and external costs, relative to the values for car systems for each method and weighting scheme, calculated for 20 PJ/year of available primary wood energy by substitution of oil-based fuels (technology around year 2005) with synthetic natural gas from wood. Eg = Egalitarian, Hi = Hierarchist, In = Individualist. EI’99-In: negative value is calculated for car systems because of higher environmental impact score for SNG car compared to petrol/diesel car. Numbers at top are absolute scores for the car system comparison.

the pipeline fossil gas and the low emissions, with the exception of CO_2. SNG production and use involves higher NO_x and particulate emissions. The oil heating system has a worse impact score than the SNG system with all the evaluation methods used.

The SNG system uses a very low amount of fossil resources and therefore emits little net CO_2, but, together with methane, about twice as much GHG as the wood furnace for supplying a district heating network. The SNG system’s disadvantages compared to the direct burning of the wood originate mainly from its lower overall chain efficiency as a result of the additional processing, and the need for substantial energy for the compression of the gas, which, if supplied from external sources, may add considerably to the total environmental burdens. Higher particulate emissions penalize the direct combustion of wood chips. However, if the plant were equipped with an electrostatic precipitator for efficient particulate removal, the overall ecological impacts of this system would be lower than, or at least comparable to, the impacts of the SNG heating system, with every methodology used. The relative score of SNG-based systems could be further improved by considering co-production of heat, power, and SNG in an SNG production plant, which would increase the overall efficiency of the system and decrease the impact of using power from the electricity grid. Anyway, a crucial advantage of SNG compared to wood remains its easier distribution to final customers through the natural gas network.

Using GHG, external costs, and the LCIA EI’99 perspectives with relatively high weight on fossil energy resources, the passenger car system fuelled by SNG has the lowest environmental impact score compared with the average car systems in 2010 burning conventional fossil fuels. When neglecting the use of fossil resources and weighting more strongly the use of metal resources, the SNG system is valued nearly as ecologically efficient as natural gas. Car and road infrastructures have a large influence on the cumulative environmental damage per person kilometre. Only when using the EI’99-Individualist perspective, which strongly weights mineral resource depletion, the use of a compressed gas tank leads to a higher total environmental impact for natural gas and SNG cars than petrol/diesel cars. However, this perspective appears the least appropriate to compare energy systems including fossil systems.

In summary, when strongly weighting the use of fossil resources or considering GHG or external costs, the renewable SNG fuel is the best performer; in the opposite case, the natural gas system is valued best. This corresponds to results from other studies about or including biofuels [10,12,13], which indicate the possibility of a substantial reduction of GHG emissions and fossil resource consumption compared to conventional fuels, at the expense of increased emission of different pollutants and other environmental issues.

Nearly all the methods applied suggest the preferential use of SNG to fuelling passenger cars rather than burning it in heating systems, as the amount of saved ecopoints, CO_2-equivalents, or external costs for substitution of current oil-based technologies is larger for cars.

A comprehensive comparison of all alternative uses of energy wood would require the consideration of co-generation. Moreover, evaluation of sustainability should consider economy as well as social indicators besides the ecological ones. A multi-criteria analysis would have to be performed for the purpose of such a multi-dimensional evaluation.

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